Development and Verification of a Comprehensive Community Model for Physical Processes in the Nearshore Ocean

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LONG-TERM GOAL

Our goal is to develop a comprehensive, verified community model that predicts nearshore hydrodynamics, sediment transport, and seabed morphology changes given offshore wave conditions and initial bathymetry.

OBJECTIVES

The basic scientific objective is to synthesize understanding of physical processes in the nearshore ocean by developing a model for

- waves and resulting radiation stresses and mass fluxes over evolving coastal bathymetry and currents
- wave-induced circulation
- sediment transport and morphological evolution

An additional objective is to test model components and the full community model with field observations.

APPROACH

Our approach is to develop a tightly-coupled system of individual model components, or modules. We are utilizing a framework where wave processes are distinguished from wave-averaged processes by means of a suitable time average. The resulting set of modules and their functions are:

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14. ABSTRACT
Our goal is to develop a comprehensive, verified community model that predicts nearshore hydrodynamics, sediment transport, and seabed morphology changes given offshore wave conditions and initial bathymetry.

15. SUBJECT TERMS

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1. wave module - calculation of second- and third-moment wave properties, including frequency-directional spectra, radiation stresses, and wave skewness and asymmetry
2. circulation module - calculation of wave-driven circulation and turbulence levels
3. seabed module - calculation of local sediment fluxes and seabed changes resulting from flux divergences, and characterization of bed geometry

A model backbone will allow interaction and feedback between the individual modules and provide an interface to users. Candidate models to be used within each module are being investigated and tested. The model backbone will be constructed as an open architecture with a documented set of required inputs and outputs for each component, allowing users to provide alternative formulations for each module.

Wave modules based on energy balances and on frequency domain Boussinesq or mild-slope equations are being investigated. Phase resolving formulations will allow detailed time series of waves to be simulated, and stochastic approaches will allow waves over large nearshore regions to be modeled. Breaking wave dissipation will be included to model waves propagating across the surf zone.

Circulation will be modeled with SHORECIRC (SC) and the Princeton Ocean Model (POM). SC solves the short-wave averaged equations including the 3-dimensional structure of mean and infragravity band currents using forcing and mass flux calculations provided by the wave module. POM is a finite-difference approximation to the hydrostatic primitive equations with a free surface, and includes equations for continuity, momentum, temperature, and salinity.

The seabed module will model the local flux of sediment and the evolution of seafloor sedimentology and morphology. Field observations are being used to develop models for sediment flux driven by near-bottom velocities. Conservation of mass allows sediment flux calculations to be used to predict changes in large-scale nearshore bathymetry. The effects of bedforms such as ripples and megaripples will be incorporated into the modules.

Model components and the full community model will be tested by comparison with field observations of waves, currents, sea floor morphology and bathymetric evolution observed at a variety of field experiments.

WORK COMPLETED

Three group meetings have been held to organize activities and review results. Working groups have been formed in the areas of (1) surface wave dynamics, (2) wave-induced circulation and turbulence, (3) sediment transport and seabed morphology, and (4) verification and data assimilation. Groups (1)-(3) are pursuing the development and testing of individual modules with the goal of advancing the science in each, as well as defining how each module will interact most effectively with the other model components. Group (4) is testing and calibrating existing models, and assembling a WWW site for field data that can be used by the NOPP partners to test individual modules.

The parabolic wave model REF/DIF S has been extended to serve as a wave driver coupled with the SC circulation model, and will be used in conjunction with the planning effort for the NCEX field experiment. In addition, a new time-domain wave driver based on a nonlinear Schrodinger equation has been developed and is being applied to the study of unsteady currents driven by wave groups. Work is underway to test the SC model under forcing from wave groups. Existing laboratory measurements with wave groups optained in a 1-D horizontal wave flume at CACR are being used to test the model's

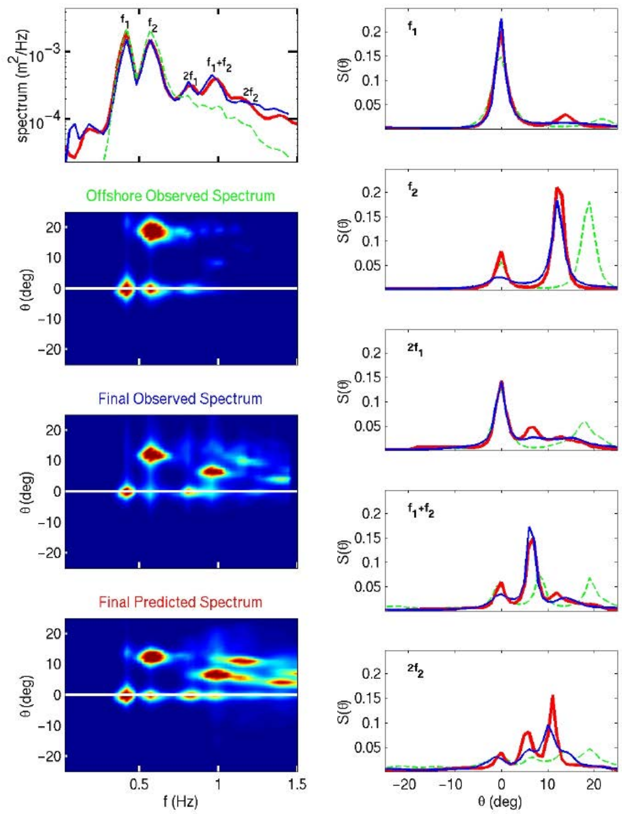

Figure 1: Example comparison of measured (Elgar et al, 1993) and predicted evolution of the frequency-directional wave spectrum on a plane beach. The color panels show (from top to bottom) the initial bimodal spectrum in 0.4 m depth with two wave systems arriving from different directions, and the observed and predicted shoaled spectrum in 0.16 m depth. The upper left panel shows the measured (blue) and predicted (red) frequency spectrum. The dashed curve is the initial spectrum. The panels on the right show measured and predicted directional distributions at the incident wave peak frequencies and the associated sum frequencies (same format).

capability to reproduce the effects of wave groupiness, time varying break points etc. This situation leads to the generation of unsteady infragravity waves in the wave flume.

The effect of nonlinear wave-wave interactions between triads of wave components has been examined for shoaling wave trains. The stochastic model of Herbers and Burton (1997) was extended into the surf zone using a heuristic parameterization of wave breaking dissipation and an improved closure approximation that allows for a relaxation to Gaussian statistics over distances comparable to the surf zone width, while retaining the quasi-normal approximation outside the surf zone. The model was tested through extensive comparisons with data from both laboratory (Figure 1) and field (DUCK94, SandyDuck) experiments. Work is in progress to extend the model to deeper water and beaches with weak alongshore depth variations.

A curvilinear version of the SC model has been developed and is presently being tested. A spectral solution of the depth-varying portion of the motion has been implemented in existing Cartesian version of SC, and will allow for the implementation of more accurate turbulence closure schemes. Work on

development of a reference version of the Cartesian SC model was essentially completed last year, and the code along with a manual was made available to the NOPP group of PI's for testing and comment. Numerous comments and suggestions have been received including various bugs which have been corrected in the code. SC version 2.0, which consists of a modified version of the REFDIF wave driver and the circulation component, will be placed on the CACR web site to make it available to registered users in the general community.

The Princeton Ocean Model (POM) has been adapted for applications to wave-averaged circulation by adding parameterized forcing represented by gradients in the radiation stress tensor. These forcing terms are partitioned appropriately as either surface stresses or as depth- independent body forces. Additional forcing related to rollers and the effects of wave-induced mass flux are included. Different turbulence closure schemes including Mellor-Yamada and k- epsilon schemes are being tested. Surface boundary conditions for the turbulence quantities at the surface that include the effects of breaking waves have been implemented. The Styles and Glenn (2000) wave-current bottom boundary layer model that parametrizes the effect of waves on the bottom stress has been embedded. Other wave-current bottom boundary models (Mellor, personal communication; Soulsby et al., 1993) are also being tested. Initial studies focus on alongshore-uniform flows with spatial variations in the across-shore (x) and vertical (z) directions. Comparisons with data from the Duck94 experiment have being made. Preliminary three-dimensional studies of shear instabilities in the alongshore current have been completed. Three-dimensional wave radiation stress terms have derived for inclusion into the momentum equations of ocean models.

It has been learned (Mellor 2001) that it is possible to augment the turbulence production term in the Turbulence Kinetic Energy equation in any closure model to account for the effects of surface wave induced oscillations on the mean current. With the help of numerical modeling, the augmented production has been derived as a function of vertical distance from the bottom, oscillation frequency and amplitude, angle between the wave number vector and mean current stress and the bottom roughness parameter. This information can be easily incorporated into three- dimensional ocean models.

The Bagnold/Bailard/Bowen sediment transport equations have been examined with respect to the validity of their assumptions in the nearshore environment. These equations were also applied to predict the equilibrium cross-shore profile under simple wave conditions. The model was found to generally be inadequate for the prediction of sediment transport in the nearshore region. Many of the assumptions inherent in this type of model are violated under common environmental conditions.

Sistex99 survey data have been processed in order to estimate the net sediment transport rates under a variety of wave conditions.

Two new models for sediment transport under unbroken waves have been developed and are currently being refined. The first is a model for sheet flow based upon a two-phase approach in which granular mechanics are utilized to model the highly concentrated region near the seabed. The model provides qualitative results that are consistent with the observations obtained in SISTEX99.

The second model is for suspended sediment concentration under unsteady waves above a rippled seabed. In this model, the recent history of the wave forcing is incorporated into the prediction for suspended sediment concentration. The results in a significant improvement in predictive capability over instantaneous models.

We continue to examine bed load processes in the surf zone using a discrete particle model to explore two phenomena of interest: 1) the effects of local bed slope on bed load transport rates under various

waveforms typical of the surf zone; and 2) processes that segregate particles by size and density. Segregation by size is particularly important in the swash zone at Duck NC, where gravel particles having diameters up to several mm are commonly interspersed with finer sands having typical diameters from 0.1 mm to 0.2 mm. Discrete particle simulations allow us to generalize predictions for bed load transport over sloping beds to two dimensions and for slopes approaching the angle of repose for sand, which is clearly beyond the scope of theories employing small-angle approximations. Work to date using discrete particle simulations indicates that transport rates for different grain sizes can vary by factors of two to three or more for size distributions which include a wide range of sizes. In particular, distributions including sand and gravel show the largest disparities in transport rates. Visualization of simulation results clearly indicate the operative mechanism: as grains are sheared in the bed load layer under sheet flow conditions, larger grains rise to the top of the bed load layer while smaller grains fall into relatively more protected, slower moving regions of the layer. Such ”inverse grading” (coarse grains lying above finer ones) is commonly observed in nearshore deposits and elsewhere in the geologic record. This sorting phenomenon has been extensively studied in the context of dry granular materials (e.g., Jaeger & Nagel, 1992)

RESULTS

We have implemented the random wave driver REF/DIF S to provide forcing for the nearshore hydrodynamics model SC, using the proposed modular structure of the NOPP community model by moving the calculation of wave-related quantities from the hydrodynamics model to the wave driver. The model was then applied to the NCEX domain. A model nest was created for Black’s Beach, in which wide-scale wave predictions from SWAN were incorporated into local scale wave model run using REF/DIF S. The results from this local run was then input into the SC model. Model results have indicated that persistant features, such as rips, which are driven by longshore gradients in wave conditions in the field are reproduced at least qualitatively in model results (Figure 2). We are presently testing a dynamic roller-based description of wave dissipation in REF/DIF S.

The phenomenon of shear waves (Oltman-Shay et al, 1989) has been widely studied in the literature by means of numerical modelling. Previous studies have all been conducted using depth-uniform nonlinear shallow water equations or slightly modified version of those equations. An exception is the work by Putrevu et al. (1998) which analysed the effect of the 3-D current structure which has also been found responsible the major part of the lateral mixing in the nearshore (Svendsen and Putrevu, 1994). Inclusion of the 3-D current structure influences the conclusions of earlier investigations on shear wave generation and development. The results are very complex but generally show that the 3-d effects greatly reduce the occurance of instability of the current and play an important role in the development of the shear waves once generated.

Applications of POM to DUCK94 conditions have continued. Comparisons with the fixed array measurements of Elgar and Guza (personal communication) show good agreement. Experiments involving the wave-current bottom boundary layer model show that the strength of the alongshore current depends on this parameterization while the across-shore currents are relatively insensitive. The effects of tidal elevation change on the circulation are investigated and show, in particular, variations in the strength of the undertow over the bar and in the trough with tidal height that are in general agreement with velocity measurements from the fixed array. The model solutions at high- and mid-tide show interesting new frontal structures in the alongshore and across-shore current fields, both on the inshore and offshore sides of the bar. Preliminary three-dimensional experiments show the development of shear instabilities in the alongshore current. The frontal structure on the inshore side of the bar is found to develop strong instabilities

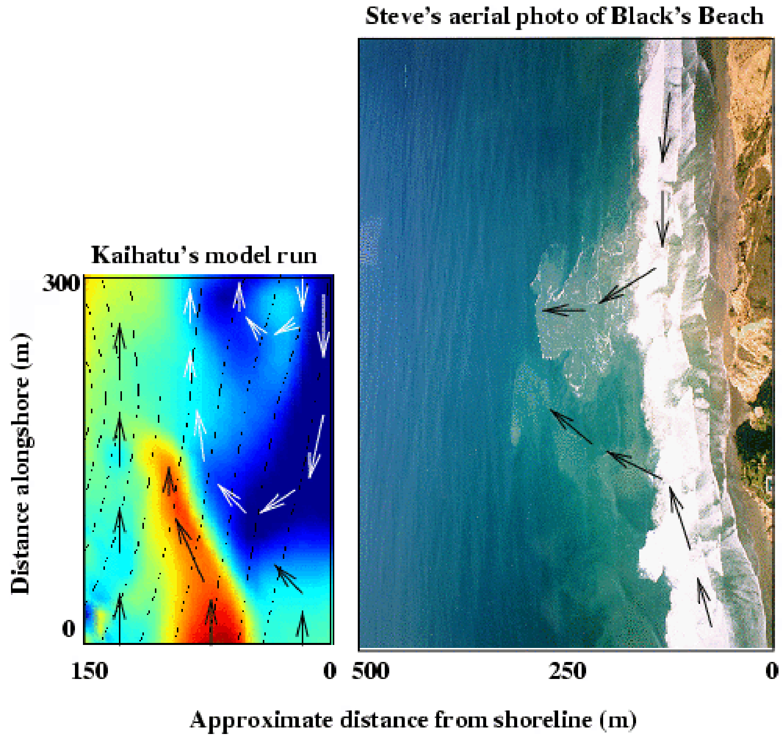

Figure 2: SHORECIRC+REF/DIF S model simulation (left) and corresponding aerial view of field conditions (right) at NCEX experiment site.

in response to small alongshore perturbations in the bottom topography. These results again demonstrate the importance of the depth-dependent across-shore circulation, through the across-shore transport of alongshore momentum, in determining basic qualitative features of the wave-averaged circulation.

With weak alongshore variation of incident waves and bathymetry, breaking theoretically results in a mean alongshore-directed force within the surf zone that is balanced by the drag of the mean alongshore current on the sea floor (Longuet-Higgins, 1970). A model based on this balance, extended to include the effects of wave rollers and lateral mixing, agrees well with the mean alongshore currents observed on two barred beaches (Duck, N.C. and Egmond, Netherlands) when the alongshore variability of the bathymetry was relatively weak (Ruessink *et al.* in press). Modeled and predicted mean alongshore currents at Egmond are shown in Figure 3. When the alongshore bathymetric variability increased, the model performance deteriorated.

The DUNE2D morphodynamic model was compared with field data from SHOWEX. A relatively simple case was used for comparison in which initial vortex ripples over a larger mega-ripple evolved to a near planar bed as storm waves intensified over a 2 hour period. The focus of the work was on bedform evolution and migration. The model was modified to accommodate an arbitrary bottom profile. However, owing to the construction of grid scheme, we were not able to generalize the forcing for the case of a migrating bed. The model gives qualitatively reasonable comparisons for migration rates (order 5 cm/hour) and evolution time from rippled to planar bed (order 2 hours).

IMPACT/APPLICATION

The model system under development will provide a comprehensive predictive tool for nearshore

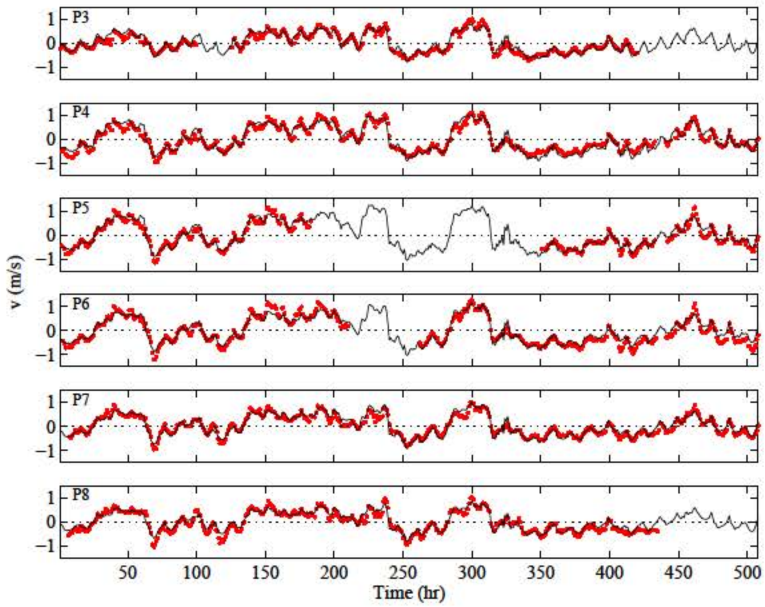

Figure 3: Time series at Egmond of measured (symbols) and modeled (curves) of mean (30-min average) alongshore current v from offshore (P3, upper panel) to onshore (P8, lower panel). The model is initialized with incident wave properties measured a few km offshore. Predicted and observed mean alongshore currents agree well at Egmond.

processes, and will have a wide range of uses in the scientific community, as well as in DoD and civil planning and operations.

RELATED PROJECTS

The investigators in the NOPP project have a range of individual projects with closely related science and modeling objectives. The NOPP model development effort benefits these other ongoing studies by increasing collaboration and exchange of results and data among the partners. The NOPP project allows results from individual investigations to be synthesized into a community-wide model for nearshore processes.

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